Millimeter Wave Digital Arrays (MIDAS)

Proposers Day

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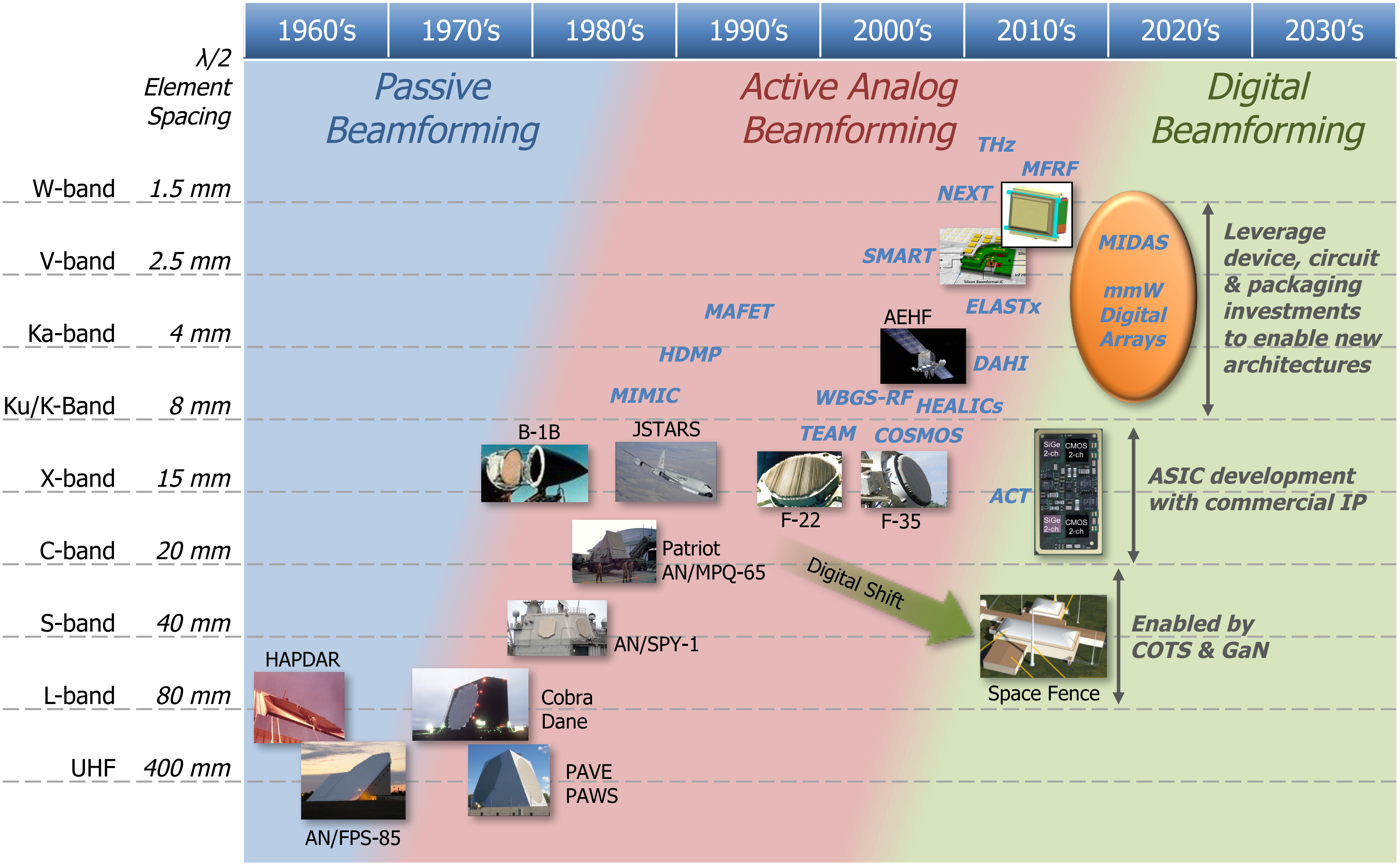
January 26, 2018

Agenda

- 0800-0900: Check-In
- 0900-0905: Welcome & Security
- 0905-0925: Contracting with DARPA
- 0925-1000: MIDAS Overview & Program Structure
- 1000-1015: Break
- 1015-1100: Q&A / Discussion
- 1100-1300: Poster & Networking Session

Program Overview

Evolution of Phased Arrays



Adapted from: J. S. Herd and M. D. Conway, "The Evolution to Modern Phased Array Architectures," in *Proceedings of the IEEE*, vol. 104, no. 3, pp. 519-529, March 2016.

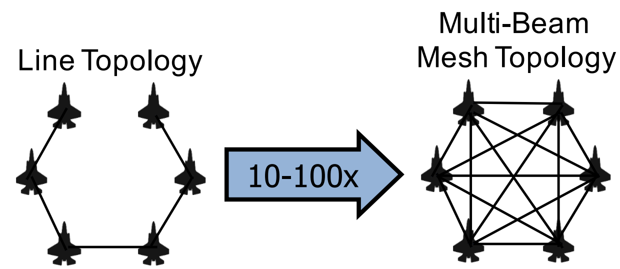
Millimeter Wave Systems

Physical Security Through Narrow Beams

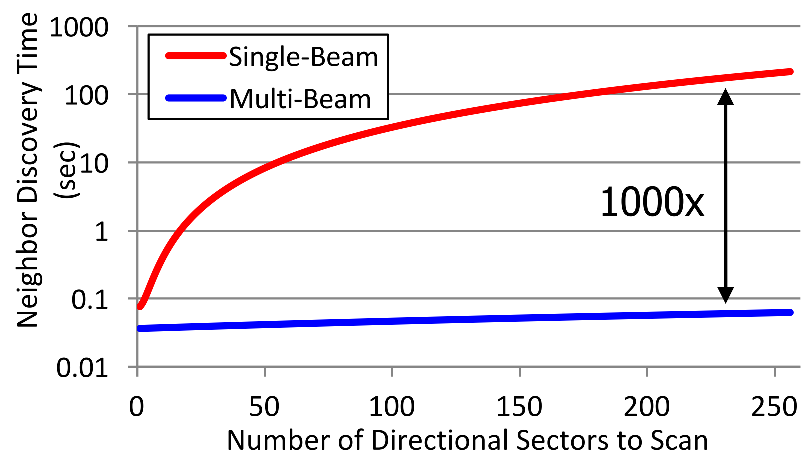
*F-22
Intra-Flight Data
Link (IFDL)*

*F-35
Multi-function
Advanced Data
Link (MADL)*

Increased Throughput & Reliability



Decreased Discovery Time



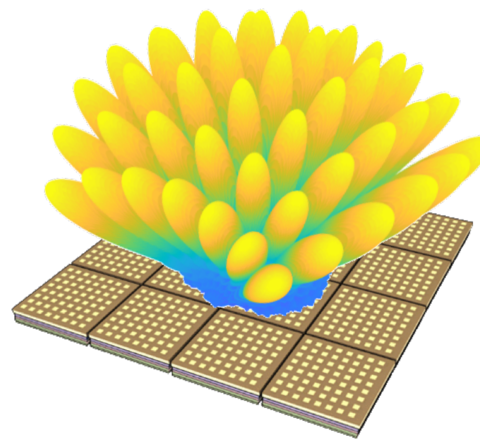
Millimeter wave links provide physical security, but pose networking challenges

Multi-Beam Digital Arrays at Millimeter Wave

Provide 4π Steradian Coverage for Multi-Beam Networked Communication

- High-gain in all directions for improved network performance
- Wide bandwidth & frequency agility to adapt to future needs

The Common Digital Array Tile at Millimeter Wave



2 Core Tech Areas

- Digital RF silicon tile at 18-50 GHz
- Wideband antenna & T/R components

Scalable Solution for Multiple Applications

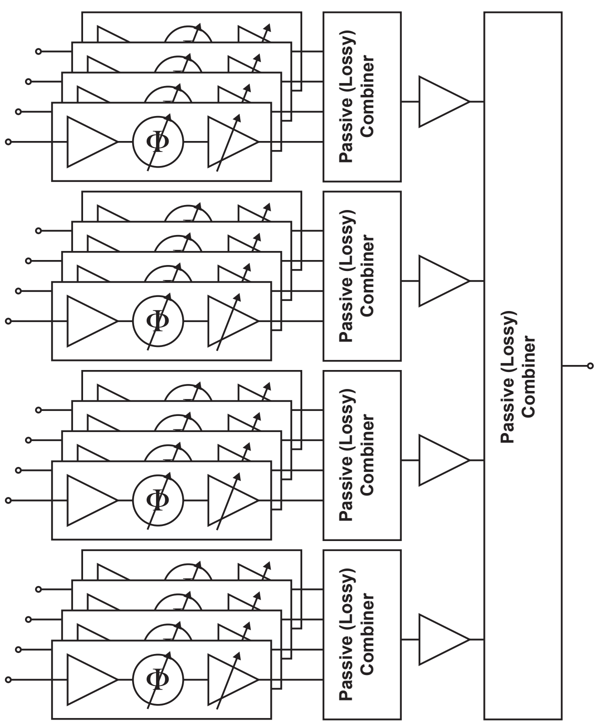
- Line-of-sight tactical communications
- Low-profile SATCOM
- Emerging LEO SATCOM

Dominate the millimeter wave spectrum with wideband digital beamforming

Millimeter Wave Phased Arrays

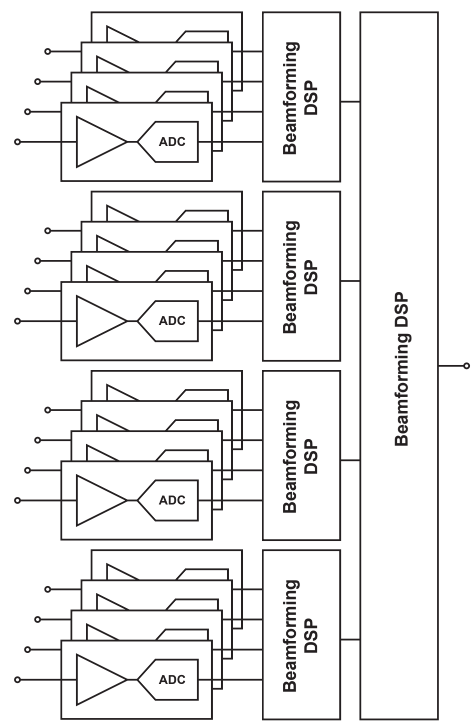
Analog Beamforming

- Lowest power implementation
- Single mixer/ADC after beamforming
- Challenging mmW design to manage phase & loss – leads to narrowband resonant designs
- True-time-delay challenging & physically large



Digital Beamforming

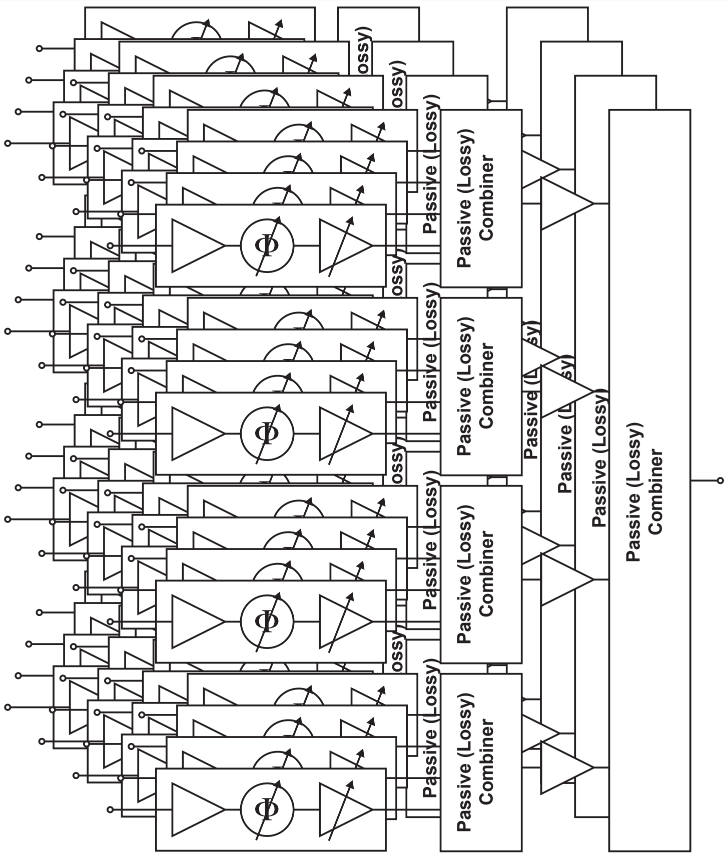
- Challenging implementation requires R&D at mmW
- Mixer/ADC at every element with beamforming DSP
- mmW design kept to antenna front-end, minimal mmW routing/loss & line amps/distortion
- Digital true-time-delay & multi-beam support



Multi-Beam Beamforming

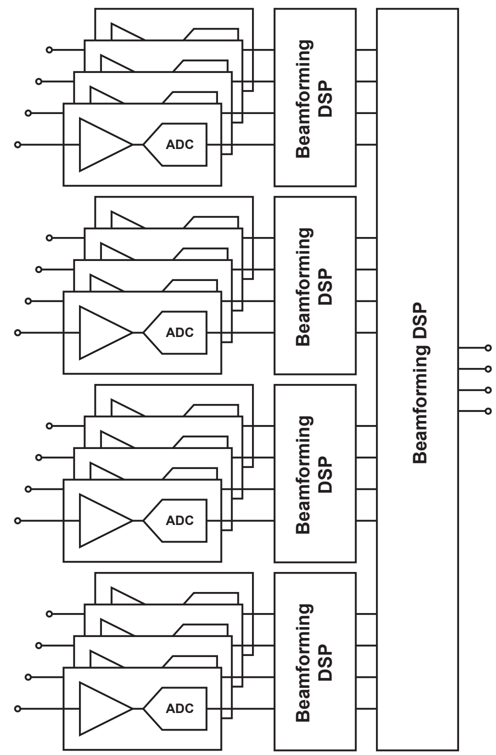
Analog Beamforming

- Multiple copies of analog beamformer
- Power directly increases with number of beams
- Size directly increases with number of beams
- Not scalable



Digital Beamforming

- No change in RF front-end with number of beams
- Size/power impact of additional DSP is small and scales with technology
- Size/power scalable if front-end can be implemented



Program Overview

Program Objectives

- Explore the extent to which ***multi-beam systems*** can be employed at millimeter wave over extremely wide ranges of frequencies
- ***Digitization within the array*** itself enabled by ultra compact RF & mixed-signal design at millimeter wave
- A reduction in size and power of digital transceivers at millimeter wave that meet the ***high linearity*** requirements
- Develop and demonstrate a ***tile building block*** sub-array (>16 elements) that supports scaling to large arrays in the 18-50 GHz band and does not eliminate spatial degrees of freedom within the sub-array

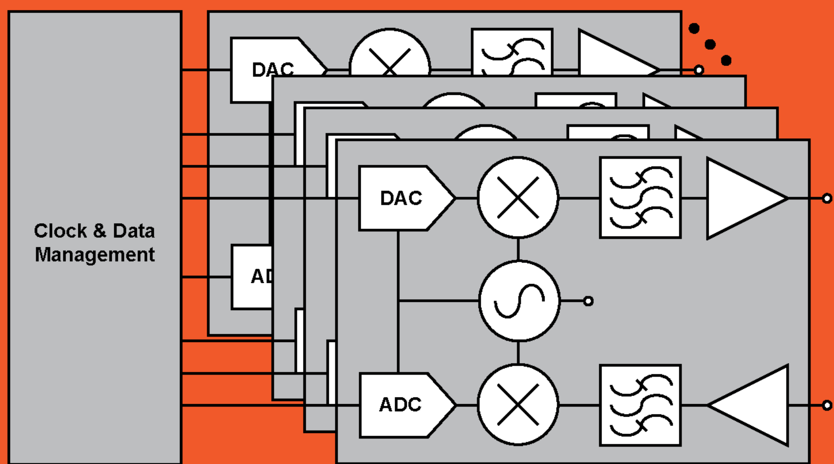
Expected Areas of Research

- Innovative sampling and frequency conversion schemes with high linearity for receive and transmit
- Distributed LO/clock generation and synchronization for each element
- Wideband/efficient transmit/receive amplifiers & radiating apertures
- Novel manufacturing to realize the integration and packaging all of these components into a scalable tile building block

Program Structure

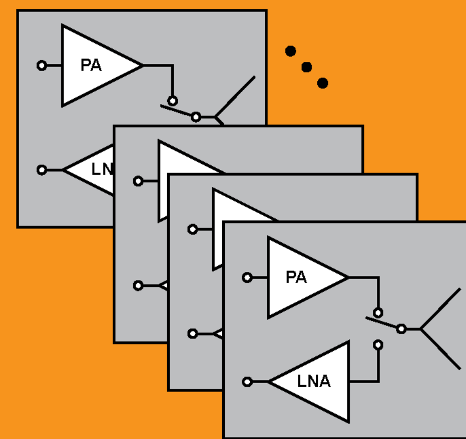
Program Structure

Technical Area 1
Wideband Millimeter Wave Digital Tiles



Tunable element-level digital transceiver tile with clock and data management

Technical Area 2
Wideband Millimeter Wave Apertures



Wideband T/R components, dual polarization radiating elements & tile packaging

Technical Area 3
Millimeter Wave Array Fundamentals

- ***Ultra-low power wide-band data converters***
- ***Potential hybrid combinations of mixing & sub-sampling transceiver architectures***
- ***Tunable & frequency selective RF front-ends***
- ***Streaming digital beamforming processing***

Program Schedule

FY 2018 | FY 2019 | FY 2020 | FY 2021 | FY 2022

CY 2018 | CY 2019 | CY 2020 | CY 2021 | CY 2022

Phase 1 – 18 mo. | **Phase 2 – 18 mo.** | **Phase 3 – 12 mo.**

MIDAS TA1
Wideband mmW
Digital Tiles

16 elements
200 MHz BW, 150 mW
Prove architecture

16 elements
2 GHz BW, 100 mW
Scale Tile Performance

MIDAS TA2
Wideband mmW
Apertures

16 elements,
6 dB NF, 2 mW/mm²
Component Demo

64 elements
4 dB NF, 5 mW/mm²
Scale Aperture Performance

256 elements
Scale Size

MIDAS TA3
mmW Array
Fundamentals

Wideband LNA/mixer, hybrid mixer/samplers, wideband PA efficiency, phase noise reduction techniques, modular manufacturing/assembly processes

Performer defined goals | Performer defined goals

Anticipated Budget: $65M

- $30-40M for TA1
- $20-30M for TA2
- <$5M for TA3

Options to Respond

- TA1 proposal or joint TA1/TA2 proposal
- No TA2 only proposals
- TA3 proposal is completely separate

TA1 Wideband Millimeter Wave Digital Tiles

Develop a wideband millimeter wave element-level digital beamformer (EDBF)

Metric	Phase 1	Phase 2	Notes
Frequency of operation	18 – 50 GHz		1
Transceiver element pitch at λ_{high}	$\leq \lambda/2$ at λ_{high}		2
Transmit & receive functionality	Yes		3
Polarization	Dual		3
Number of elements at (2D array)	≥ 16		4
Element receiver noise figure	≤ 10 dB		5
Element transmitter power density	≥ 0.1 mW/mm		6
Instantaneous bandwidth	≥ 200 MHz	≥ 2 GHz	7
Receiver IIP3	≥ 10 dBm	≥ 15 dBm	8
Transmitter OIP3	≥ 15 dBm	≥ 20 dBm	8
Beam-bandwidth product	≥ 400 MHz	≥ 3.2 GHz	9
Power consumption per channel	≤ 150 mW	≤ 100 mW	10
	Prove Architecture	*Scale Performance*	

Phase 1 → Phase 2
10x increase in bandwidth & dynamic range

TA1 Wideband Millimeter Wave Digital Tiles

1. The minimum required frequency band to cover is 18-50 GHz, supporting additional bandwidth below or above this band is also acceptable.
2. It is expected that in a tile configuration, to minimize grating lobes, while meeting the desired scan performance as outlined in TA2, it will be necessary that each dual-polarized element be spaced on grid at a half of a free space wavelength or less at the highest frequency, i.e. **≤3 mm at 50 GHz**.
3. It is required to implement two polarization channels on both transmit and receive to support emerging MIMO coding schemes, active polarimetric sensing or polarization calibration over scan angle as well as legacy linear, left and right hand circular polarizations.
4. Number of elements ≥16 corresponds to the minimum number of spatial channels. This implies **≥32 transceiver channels** to support dual polarization operation.
5. The noise figure is to be measured de-embedded to the RF pads of the tile integrated circuit. This will include the noise figure of the **entire receive chain from RF to bits** and may contain the effects of any switches, amplifiers, mixers, analog-to-digital converters (ADCs), or digital signal processing (DSP) decimation strategies.
6. The transmit power is to be measured de-embedded to the RF pads of the tile integrated circuit. This is specified as a frequency independent number that assumes the radiators will be on a regular grid in an array. For example, if the tile is designed to support 18-50 GHz and the pitch is chosen to be 3 mm, then the power per element would be 0.1 mW/mm^2 x 9 mm^2 = **0.9 mW or -0.5 dBm**. If instead, the design, was chosen to support 18-100 GHz, then the pitch of each element must shrink to 1.5 mm, but the power per element is also reduced by a factor of 4x or 6 dB, making the required power per element only -6.5 dBm, which produces the same power density at all frequencies.
7. Instantaneous bandwidth is the **digitized bandwidth after any frequency conversion, sampling, filtering or decimation**. This is the bandwidth that will be post/pre-processed by any Rx/Tx beamformer.
8. It is expected the harmonically related intermodulation distortion will be the dominate source of non-linearity for the receiver and transmitter, especially after digital beamforming and therefore the IIP3 and OIP3 is specified for the receiver and transmitter respectively. In the case of both the IIP3 and OIP3, these are in-band measurements.
9. Beam-bandwidth product is chosen to allow a range of potential performance trade-offs depending on the application. At one extreme is 1-2 beams at the full element bandwidth however the other extreme would be to provide many spatial degrees of freedom at a reduced bandwidth for signal search and link acquisition applications. For example, with 16 spatial degrees of freedom and single polarization, 25 MHz of bandwidth per beam should be achievable in phase 1 with a 400 MHz beam-bandwidth product. Likewise, in phase 2, 200 MHz of bandwidth should be achievable for 16 beams. Beamforming strategies will be left to performers to propose. Some strategies may warrant DSP hardware intimately integrated within transceivers in the tile building block, while other strategies may be best addressed with package level DSP implemented under TA2 after data is moved off of the tile. The purpose of specifying the beam-bandwidth product is to guide proposers with respect to the required I/O throughput.
10. This is the total power consumption when in transmit or receive mode. It is not expected that a tile will need to transmit and receive simultaneously (STAR), so only the transmitter or receiver will be in use at any given time. If the tile is designed to support 16 elements, or 32 channels, then this number is the **total power consumption of the tile (in Tx or Rx mode) divided by 32**. This metric should be met in both transmit or receive mode

TA2 Wideband Millimeter Wave Apertures

Develop array of wideband T/R front-ends & radiators integrated with TA1 EDBF

Metric	Phase 1	Phase 2	Phase 3	Notes
Frequency of operation	18 – 50 GHz			1
Element pitch	≤ $\lambda/2$ at λ_{high}			2
Transmit & receive functionality	Yes			3
Polarization	Dual			3
Scan performance	≥ ±60°	≥ ±70°	≥ ±70°	4
Number of elements (2D array)	≥ 16	≥ 64	≥ 256	5
System noise figure	≤ 7 dB	≤ 4 dB	≤ 4 dB	6
Radiated power density	≥ 2 mW/mm^2	≥ 5 mW/mm^2	≥ 5 mW/mm^2	7
Target Power Amplifier Efficiency	≥ 35%	≥ 45 %	≥ 45%	8
	Prove Architecture	*Scale Performance*	*Scale Size*	

Phase 1 → Phase 2
7 dB increase component performance
with improved efficiency

TA2 Wideband Millimeter Wave Apertures

1. The minimum required frequency band to cover is 18-50 GHz, supporting additional bandwidth below or above this band is also acceptable.
2. It is expected that in a tile configuration, to minimize grating lobes while meeting the desired scan performance as outlined in TA2, it will be necessary that each dual-polarized transceiver element will need to be spaced on grid at a half of a free space wavelength or less at the highest frequency, i.e. **≤3 mm at 50 GHz.**
3. It is required to implement two polarization channels on both transmit and receive to support emerging MIMO coding schemes, active polarimetric sensing or polarization calibration over scan angle as well as legacy linear, left and right hand circular polarizations.
4. A scan performance of $\pm 70^{\circ}$ is desired that is free of grating lobes and scan blindness in the **horizontal, vertical and diagonal scan planes.**
5. Number of elements ≥16 in phase 1 corresponds to the minimum number of spatial channels and is chosen to align with the performance metrics in TA1. It is expected that in phase 1, the focus will be on T/R component development, antenna design and packaging strategies. As the program progresses, phase 2 is expected to double the size in two dimensions and integrate 4 tiles from TA1. Phase 2 will also address how the tiles will interact with each other, for example clock distribution, data aggregation, beamforming/networking approach, etc. For phase 3, TA2 will demonstrate scalability and use 16 tiles to implement a ≥256 element array and refine any necessary firmware or software to implement a successful multi-beam demonstration that takes advantage of the element level digital beamforming at millimeter wave frequencies with a strong path toward technology transition.
6. In phase 1, the noise figure is to be measured assuming the simulated performance of the tile implementation from TA1. This should include any interconnect loss, or any degradation due to antenna efficiency. **In phase 2 and phase 3, these should be complete antenna to bits measured results.**
7. The transmit power is to be characterized to include interconnect losses and antenna efficiency and shall be measured with the transmit amplifier in saturation. This is specified as a frequency independent number that assumes the radiators will be on a regular grid in an array. For example, if the tile is designed to support 18-50 GHz then the pitch is chosen to be 3-mm, then the power per element would be 5 mW/mm^2 x 9 mm^2 = **45 mW or 16.5 dBm**. If instead, the design, was chosen to support 18-100 GHz, then the pitch of each element must shrink to 1.5 mm, but the power per element is also reduced by a factor of 4x or 6 dB, making the required power per element only 10.5 dBm, which produces the same power density at all frequencies.
8. The target efficiency at the end of the program is chosen such that the power amplifier consumes the same amount of power as a transmit or receive channel in phase 2 of TA1. **Note that 45 mW / 0.45 = 100 mW**. This is specifically so that neither the tile power consumption nor the PA power consumption grossly dominate the total system power consumption. This is a very aggressive goal when considering the wide bandwidth, interconnect losses and antenna efficiency but is something that should be strived for in the design.

Expected Deliverables

- Reports with description of hardware, component lab and/or field test results
- Charts and explanation of how well system meets, exceeds or falls short of specified program goals
- Hardware deliverables as enumerated below
- Sufficient documentation and support for testing at government lab (AFRL, etc.)

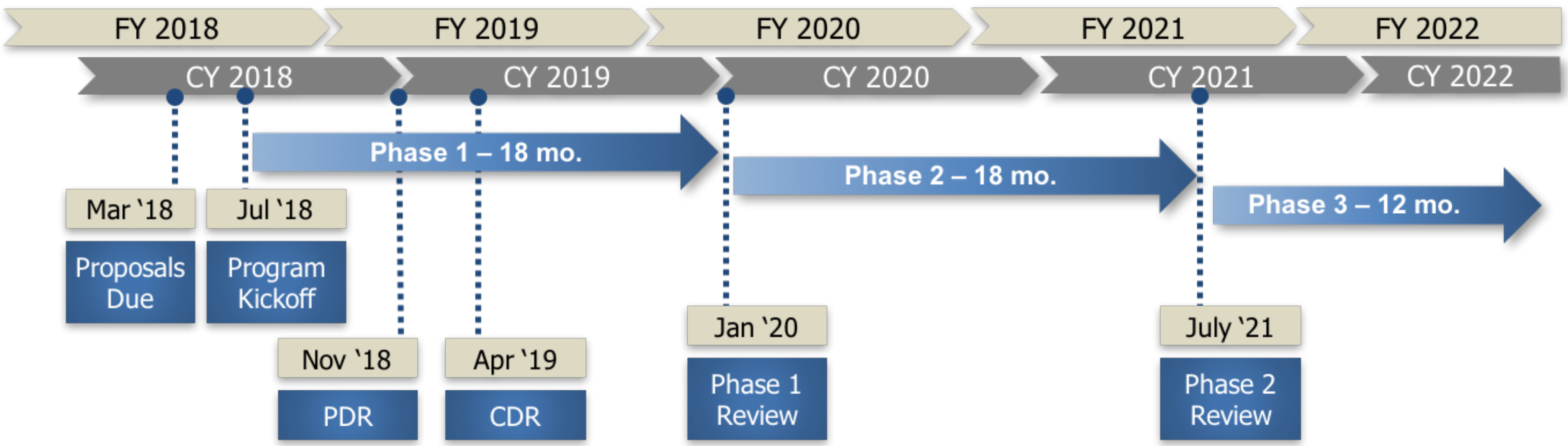
Technical Area	Phase 1	Phase 2	Phase 3
MIDAS TA1 Wideband mmW Digital Tiles	3 copies of tile	3 copies of tile	N/A
MIDAS TA2 Wideband mmW Apertures	1 copy of aperture prototype (TA1 tile not necessarily installed)	1 copy of integrated TA1/TA2 aperture	1 copy of scaled aperture
MIDAS TA3 mmW Array Fundamentals	Not required		N/A

Proposal Evaluation Criteria

<u>In Order of Importance:</u>

1. Overall Scientific and Technical Merit
2. Proposer's Capability and/or Related Experience
    - Collaborative efforts/teaming are strongly encouraged. As the program emphasizes multidisciplinary approaches, a successful proposal must demonstrate sufficient expertise in all requisite technical specialties
    - RF system design, RF and mixed-signal circuit design in advanced CMOS processes
    - RF transmit and receive component development in compound semiconductor processes
    - Advanced packaging and manufacturing techniques to include electromagnetic design of wideband antenna arrays and thermal design considerations
    - Phased-array testing and calibration experience
    - Demonstrated capability to transition the technology to the research, industrial, and/or operational military communities in such a way as to enhance U.S. defense
3. Potential Contribution and Relevance to DARPA Mission
4. Cost Realism

Program Timeline



Important Dates

- FAQ Submission Deadline: ***March 12, 2018***
- Proposal Due Date: ***March 26, 2018***
- Estimated period of performance start: ***July 2018***

BAA Coordinator: **HR001118S0020@darpa.mil**

MIDAS Question and Answer Session

Frequently Asked Questions

Q: Does DARPA intend to have multiple awards?
A: Yes

Q: Does DARPA intend to down select the performers at each program phase and what will be the evaluation criteria?
A: DARPA plans to evaluate the technical progress against the program metrics and make program decision based on the available funding. Among the metrics, the ***element pitch and power consumption*** are the major goals to be assessed to achieve the multi-beam, scalable, element-level digital array program objective!

Q: Do you really want element-level digital beamforming?
A: Yes, as stated in the BAA for TA1/TA2, the use of analog beamforming techniques that eliminate spatial degrees of freedom at the sub-array level will be considered non-responsive to this BAA. Alternative approaches in TA3 are acceptable if technically compelling.

Image Credits

HAPDAR – https://commons.wikimedia.org/wiki/File:HAPDAR_array_installation.jpg

AN/FPS-85 – https://en.wikipedia.org/wiki/Eglin_AFB_Site_C-6

Cobra Dane – https://en.wikipedia.org/wiki/Cobra_Dane

PAVE PAWS – https://en.wikipedia.org/wiki/PAVE_PAWS

AN/SPY-1 – https://missilethreat.csis.org/defsys/an-spy-1-radar/

AN/MPQ-65 – https://en.wikipedia.org/wiki/MIM-104_Patriot

B-1B – http://www.northropgrumman.com/Capabilities/ANAPQ164Radar/Pages/default.aspx

JSTARS – https://en.wikipedia.org/wiki/Northrop_Grumman_E-8_Joint_STARS

F-22 – http://fullafterburner.weebly.com/next-gen-weapons/anapg-77-radar-modes

F-35 – http://www.mwrf.com/systems/radar-systems-make-historyAEHF –

Space Fence – https://www.globalsecurity.org/space/systems/space-fence.htm

IFDL – http://fullafterburner.weebly.com/aerospace/lockheed-f22-raptor-the-definition-of-stealth

MADL – https://www.harris.com/sites/default/files/downloads/solutions/f-35-solutions.pdf

F-35 – http://www.togethertruax.com/#sthash.P6D5bibB.dpbs www.darpa.mil